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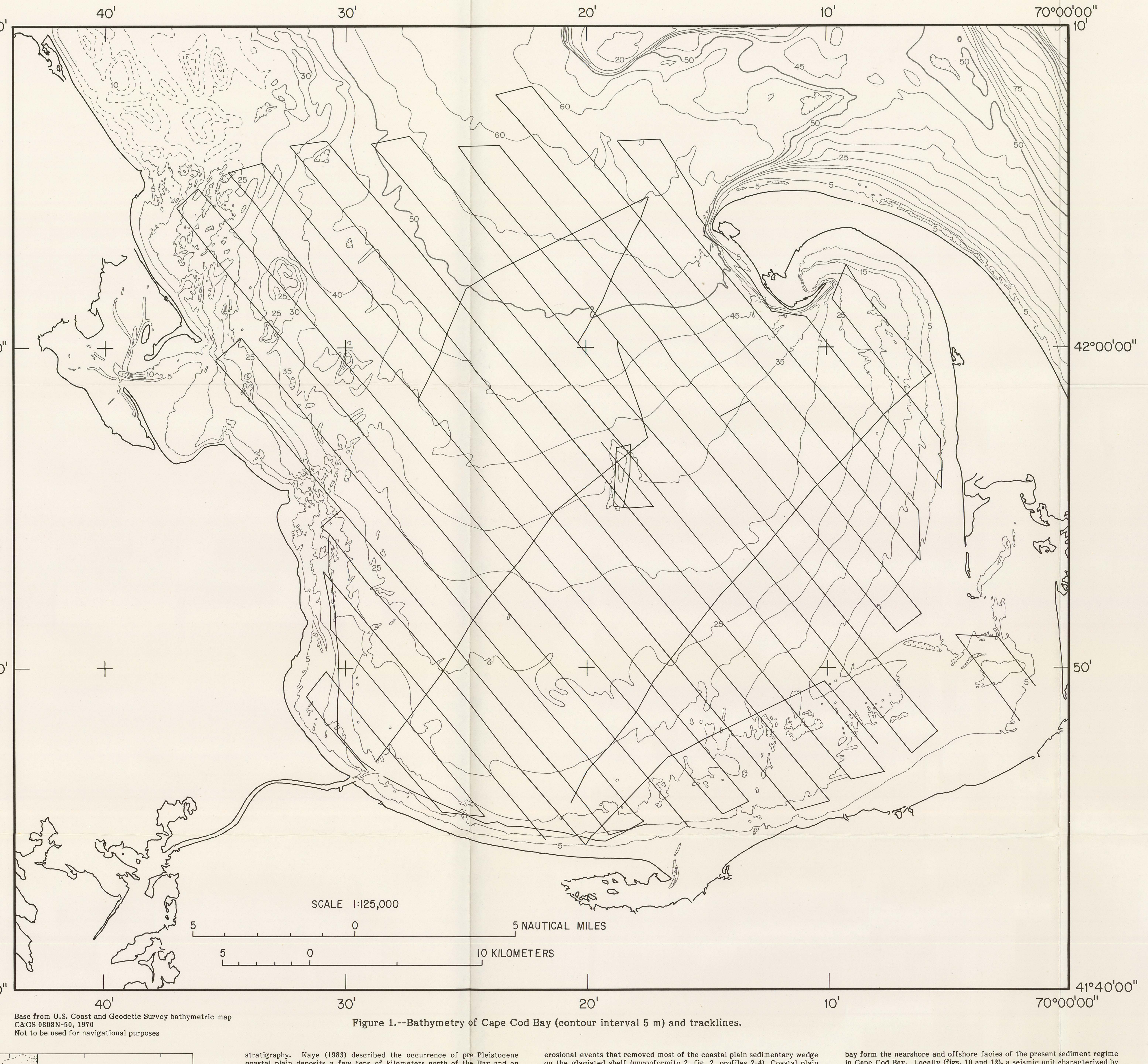
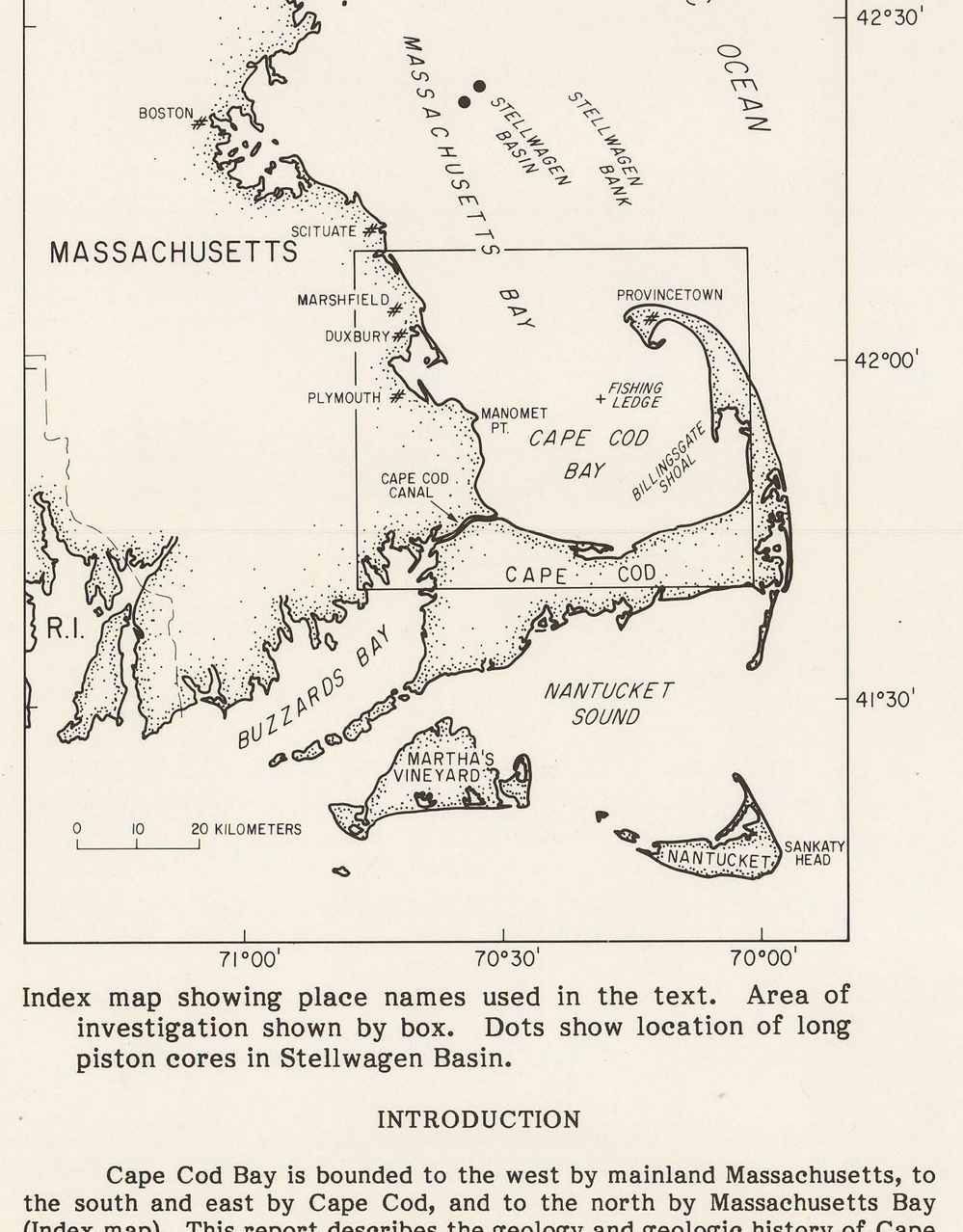
MISCELLANEOUS FIELD STUDIES
MAP MF-2118
SHEET 1 OF 4



Base from U.S. Coast and Geodetic Survey bathymetric map C&GS 0808N-50, 1970
Not to be used for navigational purposes

Figure 1.--Bathymetry of Cape Cod Bay (contour interval 5 m) and tracklines.



Index map showing place names used in the text. Area of investigation shown by box. Dots show location of long piston cores in Stellwagen Basin.

INTRODUCTION

Cape Cod Bay is bounded to the west by mainland Massachusetts, to the south and east by Cape Cod, and to the north by Massachusetts Bay (Index map). This report describes the geology and geologic history of Cape Cod Bay and expands upon an earlier open-file report by Oldale and O'Hara (1975). The interpretation of the geology and geologic history is based on about 960 km of mostly southeast-trending high-resolution seismic reflection profiles spaced approximately one nautical mile apart (fig. 1), on shallow cores, and on correlation to the geology of adjacent onshore and offshore areas. The seismic data was collected in 1973 and the vibracores were collected in 1974. The expanded report includes the initial open-file maps, a new map depicting the upper Wisconsinan stratigraphy, and a text based in part on a reinterpretation of the data from Cape Cod Bay.

Cape Cod Bay is underlain by consolidated rock of Precambrian (Proterozoic) to Triassic age that is locally overlain by mostly unconsolidated strata of Late Cretaceous and Tertiary age (here called coastal plain deposits). The bedrock surface was not penetrated acoustically and therefore bedrock types cannot be recognized and were not mapped. The coastal plain deposits, inferred from the seismic data, and the older glacial deposits that may occur below the drift of late Wisconsinan Age were too deeply buried to be sampled by the 3 m vibracore used during the investigation. The bulk of the unconsolidated deposits beneath the Cape Cod Bay are of late Wisconsinan Age and consist of drift, composed mostly of glacial-lake deposits, and marine deposits of glacial and nonglacial origin. Marine deposits of Holocene age unconformably overlie the upper Wisconsinan deposits in most parts of the bay, but conformably overlie these same deposits in the deepest parts. The unconformities represent a late Wisconsinan marine regression followed by marine transgression during the Holocene.

Acknowledgments

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METHODS

The high-resolution seismic-reflection profiles were obtained with the EG&G Uniboom system (fig. 2). The seismic data were recorded on a EPC graphic recorder using a 1/4 second sweep with the seismic signal filtered between 400 and 4,000 Hz. The cores (fig. 3) were taken using an Alpine vibracore and were used to identify the geologic nature of the seismic units where they crop out or are at shallow depths below the sea floor. Navigation for the seismic profiles and cores was by LORAN C, using an Epsco receiver. Bathymetric values (in meters) were interpolated from contour lines and bathymetric values (in feet) on the 1970 U.S. Coast and Geodetic chart 0808N-50. Travel times were converted to depth and thickness values using assumed seismic velocities of 1.5 km/sec for the water column and sediments of Holocene age, 1.8 km/sec for sediments of Pleistocene age, and 2.5 km/sec for sediments inferred to be of Cretaceous to Tertiary age. These values are based on compressional wave velocities obtained from seismic refraction studies on Cape Cod and the offshore islands (Oldale, 1969).

PREVIOUS WORK

The geologic setting for Cape Cod Bay has been established, in part, by other studies from the western Gulf of Maine and the adjacent onshore regions. An early seismic reflection study made by Hoskins and Knott (1961) largely determined the seismic stratigraphy of the bay. However, the geologic ages and origins they assigned to the seismic units have been revised on the basis of a better understanding of the offshore and onshore geology adjacent to Cape Cod Bay, and from additional seismic data within the bay and long cores from Massachusetts Bay. Seismic profiles from Massachusetts Bay (Oldale and Bick, 1987) correlated to long piston cores (Tucholke and Hollister, 1973) were used to establish the occurrence of glaciomarine mud in Cape Cod Bay (Oldale, 1988). Geologic mapping on Cape Cod (Oldale, 1982) and from the Cape Cod Canal to Duxbury and Scituate (Chute, 1965a, 1965b; Larson, 1982), established the existence of a proglacial lake in Cape Cod Bay and defined the regional onland stratigraphy. Kaye (1983) described the occurrence of pre-Pleistocene coastal plain deposits a few tens of kilometers north of the Bay and on Martha's Vineyard. He also described pre-late Wisconsinan drift in the Boston area (Kaye, 1982). Older drift and interglacial marine deposits exposed at Sankaty Head on Nantucket were described by Oldale and others (1982) and Oldale and Eskenasy (1983). A bottom sediment map of Cape Cod Bay was made by Schlee and others (1973). The chronology of deglaciation has been established from ^{14}C dates in the Gulf of Maine (Schnitker, 1988), from the Stellwagen Basin cores (Tucholke and Hollister, 1973), and from the Boston area (Kaye and Barghoorn, 1964). The history of late Wisconsinan and Holocene sea-level change has been described by Redfield and Rubin (1962), Kaye and Barghoorn (1964), Oldale and O'Hara (1980), and Oldale (1988).

GEOLOGIC SETTING

Little is known about the bedrock below Cape Cod Bay. In most places it is likely to resemble the bedrock geology of southeastern Massachusetts (Cameron and Naylor, 1976) and to include crystalline rocks of Precambrian (Proterozoic) and Paleozoic age and sedimentary rocks of Pennsylvanian age. Sedimentary rocks of Triassic age may occur beneath a significant part of the bay (Ballard and Uchupi, 1975).

Coastal plain deposits may occur locally beneath the glacial drift. Deposits of Miocene age occur atop bedrock and beneath drift at Marshfield (Index map) (Kaye, 1983). Deposits of Cretaceous and Tertiary age occur on Martha's Vineyard (Hall and others, 1980; Kaye, 1983) and beneath Nantucket (Folger and others, 1978). These deposits have been traced using seismic data northward into Vineyard Sound and Nantucket Sound (O'Hara and Oldale, 1980; O'Hara and Oldale, 1987).

The unconformity atop the bedrock, well exposed north of Plymouth, Mass. (Index map), represents more than one episode of subaerial erosion and more than one episode of glacial erosion (Kaye, 1983; Oldale, 1989). Where it is capped by coastal plain deposits, the unconformity is pre-Late Cretaceous in age, but likely no older than Jurassic. Elsewhere, it represents a subaerial erosion surface of probable middle Tertiary age that, for the most part, may represent exhumation of the older unconformity (Kaye, 1983). The bedrock and coastal plain deposits were glacially eroded during more than one Pleistocene glaciation.

Deposits of Quaternary age on Cape Cod, on the islands south of Cape Cod, along the west side of the bay, and northward to Boston provide, in large measure, the basis for understanding the post-Tertiary stratigraphic framework and the geologic setting for Cape Cod Bay. A deeply weathered till in drumlins in Boston Harbor (Kaye, 1982) and a pre-Sangamonian till at Sankaty Head on Nantucket Island (Oldale and Eskenasy, 1983) provide evidence of at least one glaciation previous to the late Wisconsinan glaciation. The age of this earlier glaciation is uncertain; it may be of early Wisconsinan age (Kaye, 1982; Stone and Borns, 1986), but it is more likely to be Illinoian in age (W. A. Newman and others, written commun., 1989; Oldale and Colman, in press). The late Wisconsinan glaciation of the region is represented by till and stratified drift. End moraine deposits on inner Cape Cod (Oldale, 1982) and west of Cape Cod Bay (Larson, 1982) indicate readvances of the late Wisconsinan ice front during the overall retreat of the ice. Outwash delta deposits on outer Cape Cod (Oldale, 1982) and along the west shore of Cape Cod Bay (Chute, 1965a; Larson, 1982) provide evidence of a proglacial lake in the bay during ice retreat. Glaciomarine mud in Massachusetts Bay has been traced into parts of Cape Cod Bay (Oldale, 1988) indicating that a marine incursion occurred simultaneously with ice retreat. The incursion was caused by isostatic depression of the crust to a point below the late Wisconsinan eustatic sea level as a result of ice loading.

Estuarine sediments that occupy valleys cut into the upper Wisconsinan deposits and that are overlain by deposits of the Holocene transgression provide evidence of marine regression during late Wisconsinan and(or) Holocene time (Oldale, 1988). The regression was caused by crustal rebound, following the removal of the ice load, that was faster than the worldwide eustatic rise in sea level.

As rebound slowed, the rising sea transgressed the region to produce a wave-cut surface that extends to the present day shore (Oldale, 1988). Deposits of sand and gravel that locally cap the transgressive surface represent beaches or bars drowned by the sea. Fine sediments that cap the transgressive surface or conformably overlie the upper Wisconsinan deposits below the lowstand shore represent marine deposition in deep water.

INTERPRETATION OF THE SEISMIC DATA

Selected seismic profiles and matching line drawings (fig. 2) illustrate the geologic interpretations used in this report. These interpretations are based on previous investigations on the Massachusetts inner continental shelf (for example, Oldale and Bick, 1987), the geology and stratigraphy revealed in studies adjacent to Cape Cod Bay (Oldale, 1982, Larson, 1982), and cores (fig. 3). The lowest reflector, stratigraphically, (unconformities 1 and 2, fig. 2) represents the bedrock surface. The underlying bedrock (Pz, figs. 2 and 12) can be traced to where it crops out along the northwesternmost shore of Cape Cod Bay. The bedrock is likely to resemble that of southeastern Massachusetts and probably consists of crystalline and sedimentary rock of Precambrian (Proterozoic) to Paleozoic age (Cameron and Naylor, 1976). Sedimentary rock of Triassic age has been inferred to underlie Cape Cod Bay from just south of Provincetown (Index map) to the vicinity of the Cape Cod Canal (Ballard and Uchupi, 1975).

The bedrock surface crops out at the sea floor in the northwesternmost part of Cape Cod Bay (figs. 4 and 12). Elsewhere it lies at depths of about 20 m to greater than 180 m below sea level (fig. 4). Bedrock occurs at shallow subbottom depths along the west and southern shores, where it reflects the general decrease in drift thickness that occurs on land from the Cape Cod Canal to Boston. It also occurs at relatively shallow depths as an east-trending bedrock high beneath inner Cape Cod (Oldale, 1969). Maximum depths occur west of Provincetown on outer Cape Cod. The bedrock surface slopes generally northeast. Two major paleodrainage systems are defined by the depth to bedrock map (fig. 4). A bedrock high trends north-northeast from a point about 7 km south of Manomet Point (Index map) and separates the two paleodrainage basins. The northwest system drained through a deep channel north of the Provincetown. The paleodrainage system in the central and southern part of Cape Cod Bay appears to have drained through a deep channel beneath outer Cape Cod, inferred to be underlain by sedimentary rocks of Triassic age (Oldale and Tuttle, 1964; Ballard and Uchupi, 1975).

The bedrock surface, locally overlain by mostly unconsolidated deposits of Late Cretaceous to Tertiary age (Kaye, 1983), was largely shaped during Jurassic to Early Cretaceous time (unconformity 1, fig. 2, profiles 2-4). It was exhumed during a fluvial erosional episode (unconformity 2, fig. 2, profiles 1 and 3-5) that occurred during middle Tertiary time (Kaye, 1983) and eroded by ice during Pleistocene glaciations, the last two occurring during Illinoian and late Wisconsinan time (Oldale and Colman, in press).

Bedrock is overlain in places by a discontinuous seismic unit without internal reflectors (Tcp, fig. 2, profiles 2-4) that is inferred to represent coastal plain deposits of possible Late Cretaceous and Tertiary ages that may be similar to those that crop out on Martha's Vineyard and in the vicinity of Marshfield (Index map) described by Kaye (1983). The coastal plain deposits are up to 100 m thick (fig. 5) and form isolated highs beneath the glacial deposits. The reflector atop these deposits represents the erosional events that removed most of the coastal plain sedimentary wedge on the glaciated shelf (unconformity 2, fig. 2, profiles 2-4). Coastal plain deposits are shown cropping out at Fishing Ledge (fig. 2, profile 3; fig. 12), a bathymetric high in the center of Cape Cod Bay. However, a vibracore (fig. 3, core 8), indicates that the coastal plain deposits may be capped by a thin layer of gravelly mud, inferred to be till.

Three seismic units (fig. 6) inferred to represent deposits of Pleistocene age (mostly late Wisconsinan) overlie bedrock and coastal plain deposits. The oldest unit (Qdl, fig. 2, profiles 1 and 3-5) is mostly characterized by short, irregular, discontinuous internal reflectors and locally by internal parabolic reflectors. Vibracores taken where the unit crops out at the sea floor (fig. 3, cores 3 and 6) showed it to be composed mostly of sand with lesser amounts of gravel, silt to clay, and some till. The isolated parabolic reflectors may be glacial boulders sufficiently large to be resolved seismically. In places, the unit displays closely spaced, generally horizontal, rhythmic reflectors that are thought to represent mostly laminated silt and clay. The unit is interpreted to be mostly stratified drift deposited in a lake that developed beyond the ice front in Cape Cod Bay. In the nearshore parts of the bay, the drift consists of outwash sand and gravel deposited as deltas graded to the lake. Further offshore the drift is thought to be subaqueous ice-contact stratified drift and outwash deposited by meltwater discharged through tunnels along the ice front.

The second seismic unit (Qgm, fig. 2, profile 2) occurs in the northeast part of the bay, and is characterized by numerous, parallel, rhythmic internal reflectors that mimic the shape of the upper surface of the underlying seismic unit. The unit has been traced southward from Massachusetts Bay where it was described and identified as glaciomarine mud of late Wisconsinan age on the basis of samples obtained in two long cores (Tucholke and Hollister, 1973; Oldale, 1988) and by correlation to glaciomarine mud exposed above sea level from Boston northward. The mud, composed mostly of subequal amounts of silt and clay with some sand and minor amounts of gravel, is mostly rhythmically bedded and locally massive. This glaciomarine mud was first deposited from sediment-laden overflow plumes of meltwater discharged into the sea along the calving front of the retreating glacier. Later it was deposited from plumes that developed when subaerial melt-water streams entered the sea (Oldale, 1989).

The lowermost part of the drift deposits, including the glaciomarine mud, may locally overlie basal till and ice-contact stratified drift of late Wisconsinan age or possibly drift of an earlier glaciation that is thought to be Illinoian in age (Oldale and Eskenasy, 1983; Oldale and Colman, in press).

A third seismic unit (Qa, fig. 2, profile 2) occurs in the central part of the bay, north of about 41° 54' (distribution is shown by Qad and Qam in figure 6). The unit is wedge shaped; it is thickest to the south and thins to the north, indicating a southerly source. In most places, the unit is characterized by an amorphous seismic signature that lacks coherent internal reflectors. Off Provincetown, it displays long, continuous, dipping, internal reflectors that resemble delta foreset beds (fig. 2, profile 2; fig. 6). The unit unconformably overlies the glaciolacustrine deposits and conformably overlies and in places interfingers with the glaciomarine mud. A single short vibracore, taken where the unit crops out, indicates that it is composed of sand (fig. 3, core 9). At Provincetown, a deep borehole (Zeigler and others, 1960) may have sampled this amorphous unit and indicated that it consists of poorly sorted silty sand containing the foraminifera *Elphidium*, which is found in the glaciomarine mud and is characteristic of the upper Wisconsinan marine deposits in the Gulf of Maine (Oldale, 1988). This amorphous unit is inferred to represent an upper Wisconsinan marine deposit of nonglacial origin that formed when the ice front was far to the north, possibly near Boston (Oldale, 1988). It has been considered to be in part debris-flow deposits formed as unstable glaciolacustrine deposits slumped, and in part deltaic deposits graded to the late Wisconsinan low sea-level stand, formed of material derived from fluvial dissection of the outwash deltas on outer Cape Cod (Oldale, 1988). A third possibility, recently suggested by F.S. Birch (written commun., 1988), is that the amorphous unit represents an ancestral Provincetown spit, formed during the late Wisconsinan marine submergence of the outer Cape Cod drift.

The deposits of Pleistocene age are up to 120 m thick (fig. 7). They are thickest adjacent to Cape Cod and in the central part of the bay, except at Fishing Ledge where coastal plain deposits crop out or occur at shallow subbottom depths. The Pleistocene deposits are thinner along the western side of the bay where they are composed solely of drift; a similar decrease in the drift cover occurs on land from the Cape Cod Canal to Boston. They are thinnest in the northwest corner of the bay where bedrock crops out both offshore and onland (Chute, 1965a and 1965b).

The reflector atop the deposits of Pleistocene age for the most part represents two unconformities (ru and tu, fig. 2). The first unconformity (ru) is preserved as valley-like depressions in the Pleistocene surface (fig. 2, profiles 1 and 5) and is inferred to have been cut by streams during the late Wisconsinan/Holocene low sea-level stand. The second unconformity (tu) is a generally flat surface that truncates the deposits of Pleistocene age and the valley-fill deposits atop the regressive unconformity. It is inferred to be a wave-eroded surface formed as the sea transgressed to its present level during the Holocene. Both unconformities have modern analogues. The glacial drift surface beneath the estuarine deposits adjacent to Cape Cod Bay represents the regressive unconformity, and wave-eroded drift along the shore represents the transgressive unconformity. At depths exceeding roughly 60 m the reflector atop the deposits of Pleistocene age represents a conformable contact between marine deposits of late Wisconsinan Age and marine deposits of Holocene age.

Depth contours drawn on the top of the deposits of Pleistocene age (fig. 8) depict a well-developed paleodrainage system down to depths of about 60 m below sea level. It represents a complex unconformable surface cut during the late Wisconsinan/Holocene marine regression and during the Holocene marine transgression. Along the shore, where waves scour the bottom, and off the Provincetown spit, where strong tidal currents erode the bottom, the surface of the Pleistocene deposits forms the sea floor (fig. 12).

The remaining seismic units overlie the Pleistocene deposits and represent marine deposits of Holocene age. These deposits are time transgressive in that they are related to the Holocene rise in sea level. The deposits formed initially as the sea began its transgression, and modern equivalents are forming today in Cape Cod Bay and along the shore.

The oldest seismic unit assigned a Holocene age occupies valleys cut into the deposits of Pleistocene age. The unit (Qf, fig. 2, profiles 1 and 5; fig. 12) occurs above the regressive unconformity (ru) and below the transgressive unconformity (tu) and is composed of sand to clay and some peat (for example, fig. 3, cores 12 and 13). It is inferred to represent fluvial and estuarine deposits that formed in embayments drowned by sea-level rise. As sea level continued to rise, the upper part of these deposits was eroded by the transgressing surf zone.

The other three seismic units of Holocene age occur just below the sea floor and atop the transgressive unconformity. A seismic layer that is mostly acoustically transparent, but in places shows long continuous internal reflectors (Qm, fig. 2, profiles 2-4), occurs in the central and deeper parts of Cape Cod Bay (fig. 12). It represents marine sand and mud (fig. 3, cores 4 and 10) deposited offshore in quiet water environments. A seismic unit that occurs in the shallower parts of the bay (Qb, fig. 2, profile 5; fig. 12) is composed mostly of sand (fig. 3, cores 2, 7, and 11). For the most part it represents the offshore extension of the modern beach deposits, derived from the erosion of the glacial drift along the shore of Cape Cod Bay. The beach deposits and the mud in the deeper parts of the bay form the nearshore and offshore facies of the present sediment regime in Cape Cod Bay. Locally (figs. 10 and 12), a seismic unit characterized by positive relief (Qob, fig. 2, profiles 1 and 3) and in places by dipping internal reflectors occurs atop the transgressive unconformity. It is made up of sand (fig. 3, cores 1 and 5). These deposits are inferred to be relic and represent drowned bars or beaches formed at lower sea levels.

The thickness of the undifferentiated marine deposits of Holocene age is shown on figure 9. In large measure, the thickness is controlled by the morphology of the underlying surface, so that the deposits are thick where they fill valleys cut into the Pleistocene deposits and thin where they overlie uplands between the valleys. The deposits are thin to absent in the northwestern most part of the bay, where bedrock outcrops are common. They are absent off Provincetown, where strong tidal currents have exposed the underlying deposits of Pleistocene age. The thickness and distribution of the older beach and bar deposits is shown on figure 10. These deposits have been singled out because they are potential resources of sand and gravel.

The upper surface of the marine deposits of Holocene age coincides with the sea floor. In most places, the surface of the marine deposits is smooth with little or no relief (fig. 1). Locally, the older beach and bar deposits form an irregular sea floor (compare fig. 1 and fig. 10). Figure 10 shows the distribution and thickness of the older beach and bar deposits.

Total sediment thickness in Cape Cod Bay is shown by figure 11. The thickest sections reflect the distribution of the coastal plain deposits and the increase in thickness of the drift that culminates with the deposits on Cape Cod. Elsewhere, the total sediment thickness increases where the deposits fill valleys in the bedrock surface. The general decrease in total sediment thickness along the western part of the bay represents relatively thin drift atop bedrock.

The morphology of the sea floor is depicted by the bathymetric map (fig. 1). The surface is the result of recent deposition and erosion. In most places, the surface is generally flat or has low relief, the result of Holocene marine deposition that filled lows in the late Pleistocene surface. In other places, the sea floor is smooth because the transgressive unconformity is exposed at the sea floor or because the unconformity is overlain by a thin layer of marine sediments. The sea floor is rough where bedrock crops out, for example, in the northwest corner of the bay, or where older beach and bar deposits form the bottom. A bathymetric high in the center of Cape Cod Bay, Fishing Ledge, is underlain by coastal plain deposits. A bathymetric high, Billingsgate shoal (Index map), in the southeastern part of Cape Cod Bay, is interpreted to be an end moraine that was formed glaciotectonically as the ice readvanced during its general retreat from the bay (Oldale and O'Hara, 1984). Abrupt shoaling off Provincetown is the result of the progradation of the Provincetown spit into deep water.

The geologic map, including the descriptions of the map units (fig. 12), is based on interpretation of the seismic data and vibracores. The map shows the distribution of the geologic units that crop out at the sea floor or are capped by a layer of sediment too thin to be resolved in the seismic profiles. Cross sections, constructed from the geologic map, and a correlation diagram show the relative age of the map units. In addition, the cross sections illustrate the vertical relationships between the map units and major contacts, including significant unconformities. Deposits of Pleistocene age (Qd) are undifferentiated on the geologic map; however, the distribution and relative age of the units that make up these deposits of Pleistocene age are shown by the map and explanation in figure 6.

The center and deeper part of the bay is dominated by mud (Qm) of Holocene age deposited in deep water below the influence of wave action. Fishing Ledge, in the center of the bay, is interpreted to be mostly underlain by coastal plain deposits (Tcp) partly overlain by till of Pleistocene age (Qd) and older beach deposits (Qob). The older beach deposit was formed when Fishing Ledge was exposed above sea level and formed an island within the bay. Both the deposits of Pleistocene age and fluvial or estuarine deposits of Holocene age (Qf) crop out northwest of Provincetown where swift currents have eroded the sea floor. In the nearshore the geologic map is complex. Deposits of Pleistocene age and fluvial and esturaine deposits capped by the transgressive unconformity crop out in many places. Older beach and bar deposits make up the sea floor in the southeastern and northwestern parts of the bay and may mark former shorelines. Elsewhere in the nearshore regions, Holocene beach deposits (Qb) make up most of the sea floor. Along the western shore of the bay, bedrock outcrops (Pz) characterize the sea floor in a number of places.

GEOLOGIC HISTORY

The bedrock beneath Cape Cod Bay (Pz, figs. 2 and 12) is not known in detail. In general the igneous and metamorphic rocks represent episodes of mountain building as the continents collided and the oceans closed. The sedimentary rocks represent episodes of rifting when the continents drifted apart and the ocean basins expanded. Coastal plain deposits within Cape Cod Bay (Tcp, figs. 2 and 12) formed along the continental margin as the latest opening of the Atlantic Ocean progressed through the Mesozoic and Cenozoic eras. They were deposited in environments that most likely resembled those occurring today on the emerged and submerged coastal plain south of the limit of the late Wisconsinan glaciation. Unconformities on the bedrock and atop the coastal plain deposits (1 and 2, fig. 2) represent subaerial erosion during Jurassic--pre-Late Cretaceous time and during middle Tertiary time. Later, these surfaces were further eroded during two or more Pleistocene glaciations.

The Quaternary history of Cape Cod Bay is represented by the glacial and marine deposits that lie above the unconformites on the bedrock and coastal plain deposits. The oldest sediments may have been deposited by a pre-late Wisconsinan glaciation of probable Illinoian age and in the sea during a near present sea-level stand of Sangamonian age, and may be similar to the till and marine deposits exposed at Sankaty Head on Nantucket (Oldale and others, 1982) and to the till in the drumlins of Boston Harbor (Kaye, 1982).

The advance and retreat of the late Wisconsinan Laurentide glacier is a major factor in the geologic history of Cape Cod Bay. The advance is not well dated, but probably occurred about 21 ka (Stone and Borns, 1986). The retreat probably began shortly after 18 ka, as glaciomarine clay of about that age occurs in a basin just to the east of outer Cape Cod (Schnitker, 1988). The ice eroded the bedrock, coastal plain deposits, and deposits of previous glaciations and interglaciations. The eroded material was incorporated into the drift deposited during the retreat of the last ice. As the Laurentide ice retreated from the Cape Cod Bay region, it was characterized by lobation. From west to east, the lobes were the Buzzards Bay lobe, the Cape Cod Bay lobe, and the South Channel lobe that occupied a position to the east of outer Cape Cod. As the ice retreated from Cape Cod Bay, a proglacial lake developed, dammed by ice and the drift that makes up Cape Cod and by high land to the west of the Bay. Sediment-laden meltwater from the Cape Cod Bay and South Channel lobes entered the lake to form the glacial lake deposits (Qdl, fig. 2, profiles 1 and 3-5). Meltwater from the Buzzards Bay lobe drained southwest through Buzzards Bay and did not enter the lake. Melt-water streams from the South Channel and Cape Cod Bay lobes built outwash deltas along the lake shore, graded to different lake stages as the lake level gradually dropped (Oldale, 1982). As the Cape Cod Bay lobe retreated into Cape Cod Bay, the lake increased in size. In the deeper parts of the lake, the Cape Cod Bay lobe contributed ice-contact deposits and outwash to the lake floor as melt-water discharged from tunnels at the base of the ice. The Cape Cod Bay lobe readvanced out of the lake and built the Sandwich moraine. A later readvance formed Billingsgate Shoal, a subaqueous moraine that may correlate to a small subaerial moraine in the vicinity of Plymouth (Larson, 1982).

The glacial lake ceased to exist when the sea entered the bay, probably through the bathymetric low between outer Cape Cod and Stellwagen Basin (Index map), during the late Wisconsinan marine incursion. From that point onward, the retreat of the ice front and marine submergence were synchronous; as the ice retreated northward out of Cape Cod Bay and Stellwagen Basin, the sea took its place immediately. Glaciomarine deposition was characterized by subaqueous ice-contact and outwash deposition along the ice front and, more importantly, by deposition of the glaciomarine mud (Qgm, fig. 2, profile 2) from sediment laden overflow plumes. Iceberg rafted debris formed a minor component of the glaciomarine mud until the ice front retreated beyond the marine limit, about 14 ka (Kaye, 1982). Following that event, the overflow plumes that formed as subaerial melt-water streams entered the sea constituted the sole source for the glaciomarine mud.

The upper Wisconsinan deposit, characterized by an amorphous seismic signature and locally by apparent foreset beds (Qa, fig. 2, profile 2), is not well understood. It is clearly of marine origin as it interfingers with the glaciomarine mud and its source is clearly non-glacial because it thins to the north and was formed when the ice front had retreated from Cape Cod Bay. It is inferred to have been derived from the glaciolacustrine drift and to be in part, a debris flow deposit and in part, a deltaic deposit graded to the late Wisconsinan low sea level (Oldale, 1988). It may also represent an ancestral Provincetown spit as suggested by F.S. Birch (written commun., 1988).

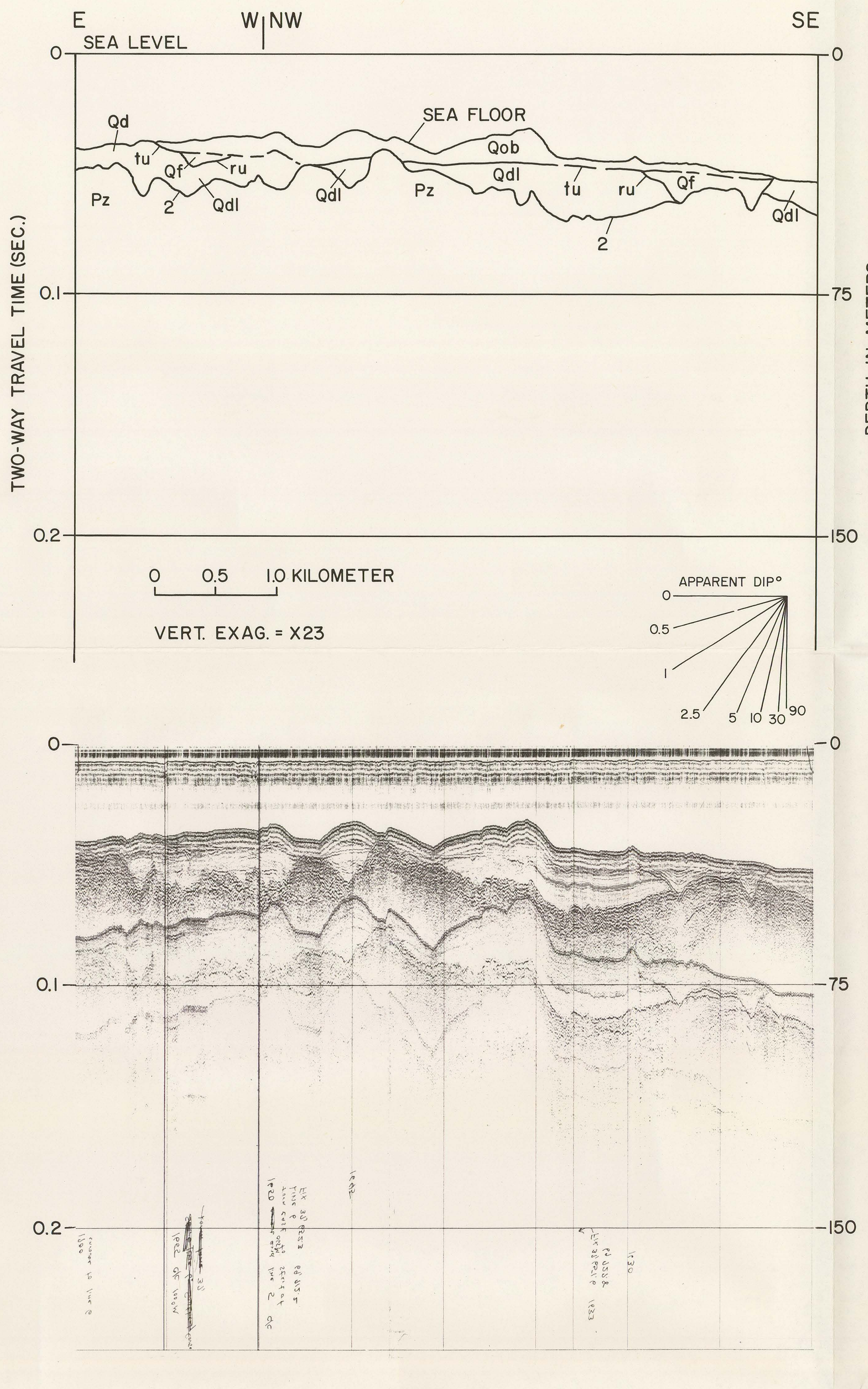
The late Wisconsinan marine incursion was caused by the glacial depression of the crust to a point below the eustatic low sea-level stand. Release of the glacial load caused the crust to rebound and shortly afterward, the sea regressed to the late Wisconsinan/Holocene lowstand of about -60 m, the lowest point at which valleys cut in the Pleistocene deposits can be recognized. Subaerial erosion formed the regressive unconformity (ru, fig. 2, profiles 1 and 5). The timing is not firmly established, but the lowstand may have occurred about 10 to 11 ka (Oldale and others, 1987). Rebound slowed through time, but the eustatic sea-level rise continued as the continental glaciers waned. Under these conditions, the Holocene transgression began and continues today. The rise in sea level was quite rapid, about 17 m/1,000 years (Oldale and O'Hara, 1980). It slowed gradually until about 2,100 years ago, when the rate dropped to about 1 m/1,000 yrs (Oldale, 1985). As the transgression proceeded, the valleys that were cut into the Pleistocene deposits during the lowstand were drowned and became estuaries. Fluvial and marine sediment, including peat, were deposited in the estuaries (Qf, fig. 2, profiles 1 and 5). The surf zone migrated shoreward, planing both the interfluvial uplands and the deposits in the valleys to form the transgressive unconformity (tu, fig. 2). During the transgression, beaches and bars formed in the nearshore, possibly when sea-level rise slowed or stopped during the overall submergence (Gayes, 1987). Many of these features were probably destroyed by wave erosion when they were drowned by the rising sea level. Those not destroyed during the transgression are represented by the submerged older beach and bar deposits (Qob, fig. 2, profiles 1 and 3). Wave erosion of the subaerial glacial deposits adjacent to Cape Cod Bay probably started about 6 ka (Zeigler and others, 1965). The eroded material formed the beach deposits (Qb, fig. 2, profile 5) in the shallower parts of the bay. Fine sand to clay winnowed from the glacial deposits by wave action and tidal currents were transported offshore. There, in quiet water, they settled to the sea floor to form marine mud (Qm, fig. 2, profiles 2-4).

SUMMARY

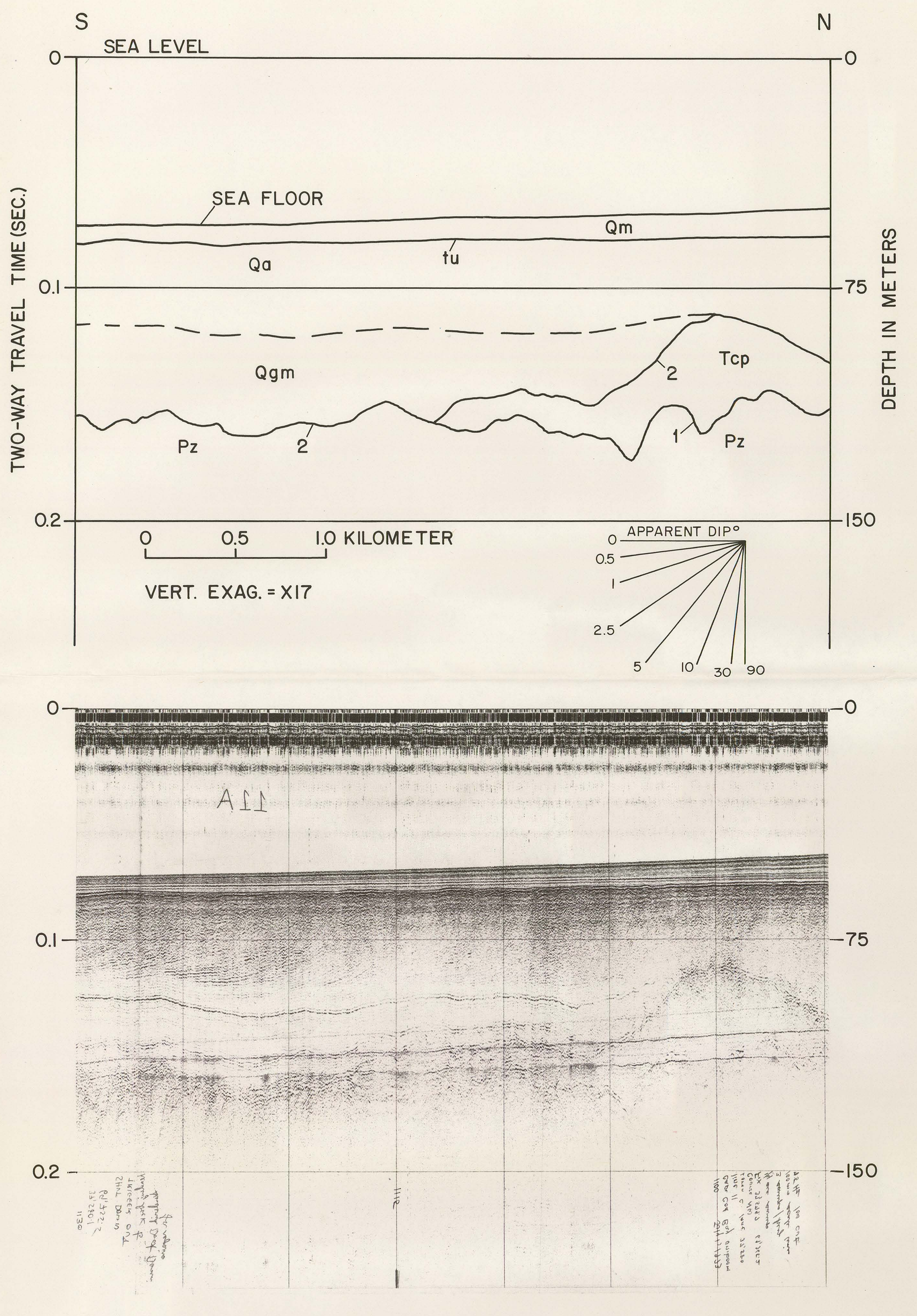
Most of the sediments within Cape Cod Bay were deposited during the retreat of the late Wisconsinan Laurentide ice sheet and during the transgression of the sea during Holocene time. Initially the sediments were deposited in a proglacial lake that developed beyond the ice front; they consist of deltaic outwash deposits and subaqueous ice-contact and outwash deposits. The lake drained when the sea transgressed the region and buoyed the ice that dammed the lake to the north. The marine incursion was the result of the crust being isostatically depressed below the late Wisconsinan eustatic sea level. Ice-front retreat and the marine incursion occurred simultaneously. The glaciomarine sediments include submarine ice-contact and outwash deposits that formed at the sea floor along the ice front, and marine mud formed when sediment carried by plumes of melt-water settled to the sea floor. The overlying nonglacial deposits of late Wisconsinan age are less well understood, possibly, they were deposited as debris flows derived from the glaciolacustrine drift, deposited as deltas derived from subaerial erosion of the Cape Cod outwash plains, or an ancestral Provincetown spit.

Sea-level change was the second major factor in the development of Cape Cod Bay. Regression followed the late Wisconsinan marine incursion. Relative sea level dropped to about -60 m as a result of crustal rebound and the marine deposits were subaerially eroded. The Holocene marine transgression followed shortly thereafter, when rebound slowed and the eustatic sea level continued to rise. Estuarine and fluvial deposits formed in the valleys, and as the surf zone transgressed the landscape, it cut the marine unconformity. Beach and bar deposits formed during pauses in the transgression. Although many of these deposits were probably destroyed as the transgression continued, some were drowned.

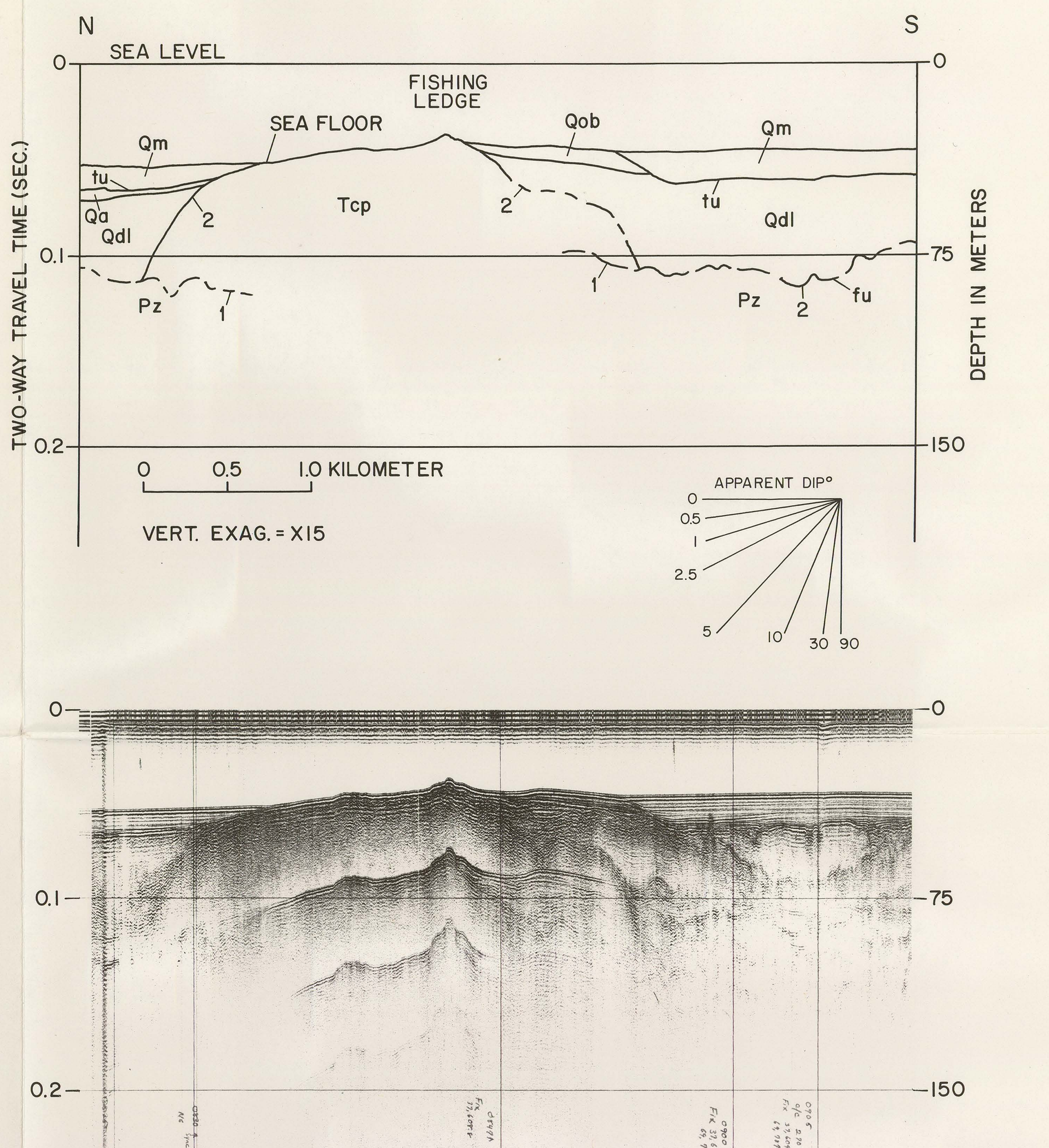
Presently, beach deposits are being formed along the shore as the sea erodes the glacial drift and redeposits the sand and gravel. Estuarine deposits are forming in the estuaries and behind barrier beaches. Marine muds, the finer fraction of the eroded material, are being deposited in the deeper water offshore. Thus, the processes related to the marine transgression are continuing, resulting in modern features along the shore that are counterparts of the submerged Holocene features in Cape Cod Bay.



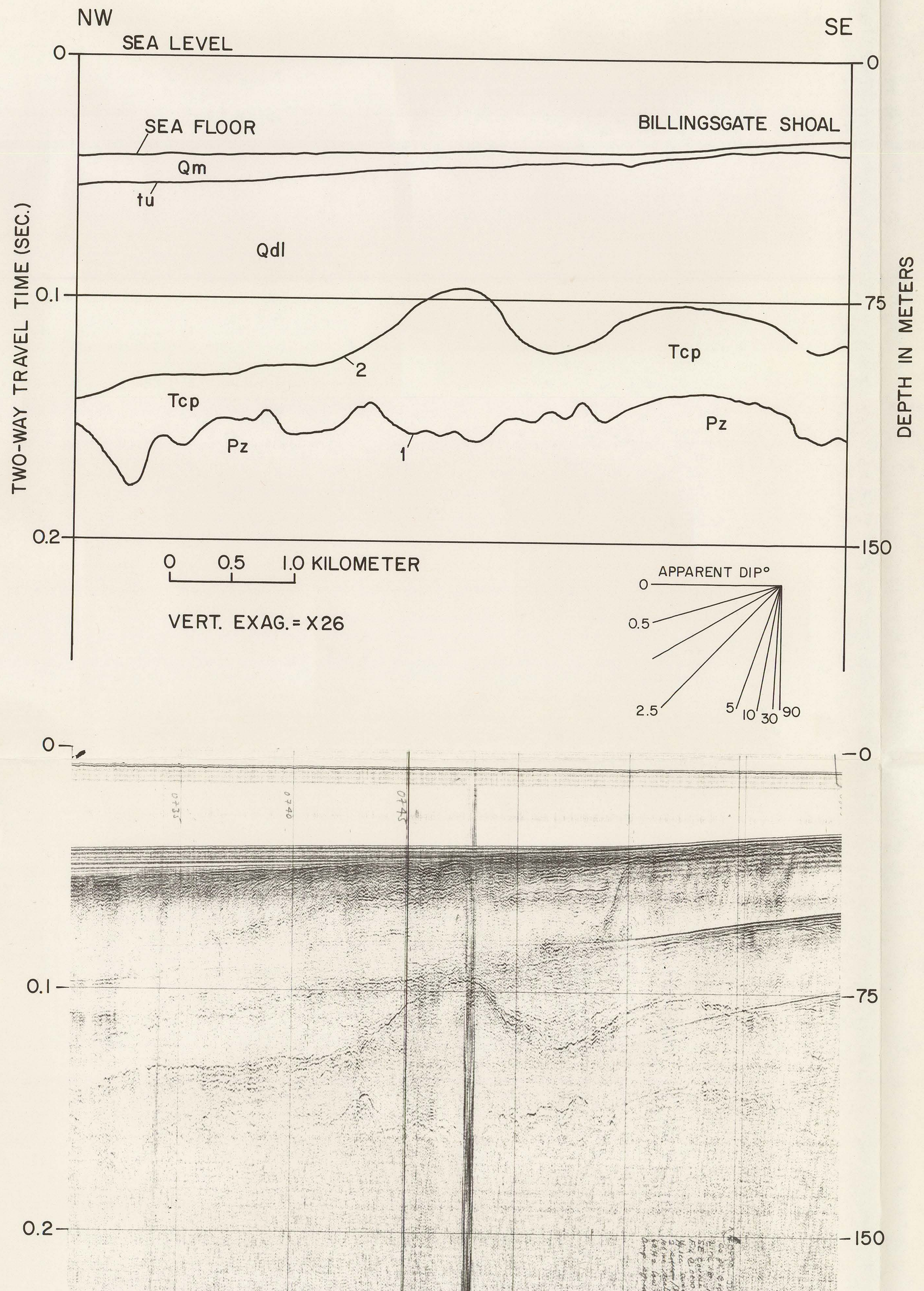
PROFILE 1



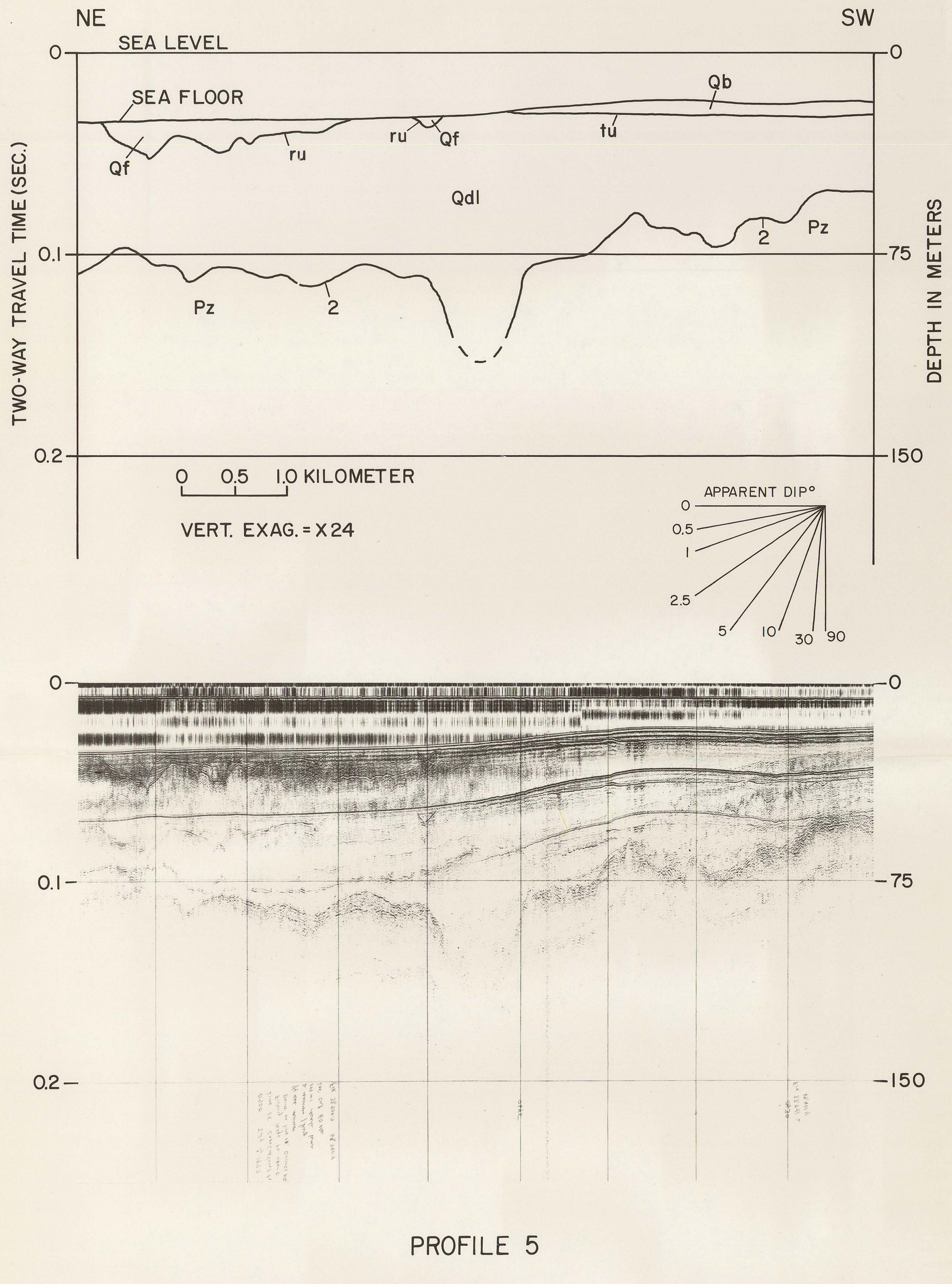
PROFILE 2



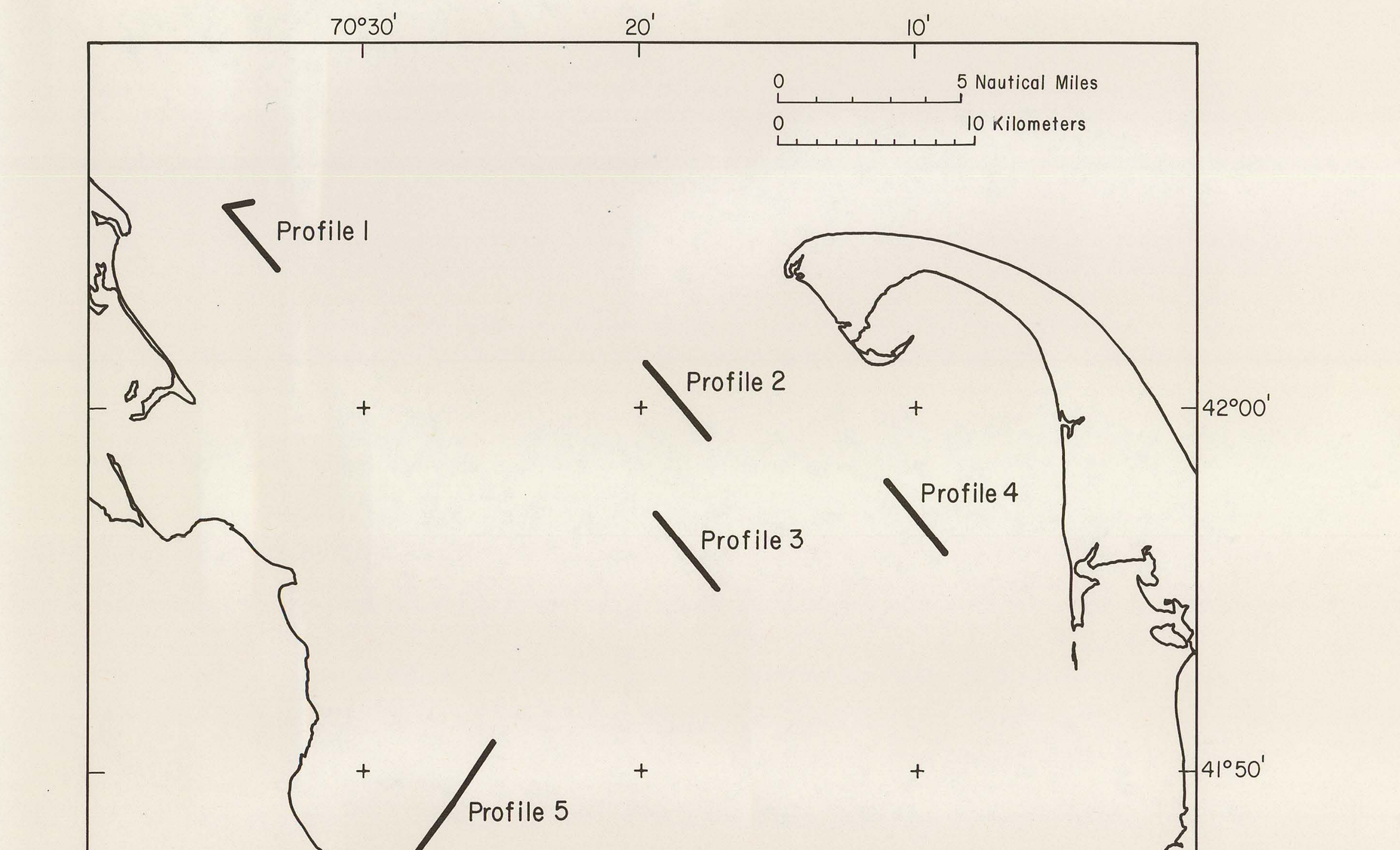
PROFILE 3



PROFILE 4



PROFILE 5



INDEX MAP

Figure 2.--Selected seismic profiles. Locations shown on index map. Rocks of Triassic to Precambrian (Proterozoic) age: bedrock (Pz), coastal plain sediments (Tcp). Deposits of Pleistocene age (mostly late Wisconsinan Age): glaciolacustrine (Qdl), glaciomarine (Qgm), and marine (Qa). Deposits of Holocene age: fluvial and estuarine (Qf), deep water marine (Qm), older beach or bar (Qob), and beach (Qb). Contacts or unconformities: atop bedrock (1), atop bedrock and coastal plain deposits (2), regressive unconformity (ru), and transgressive unconformity (tu).

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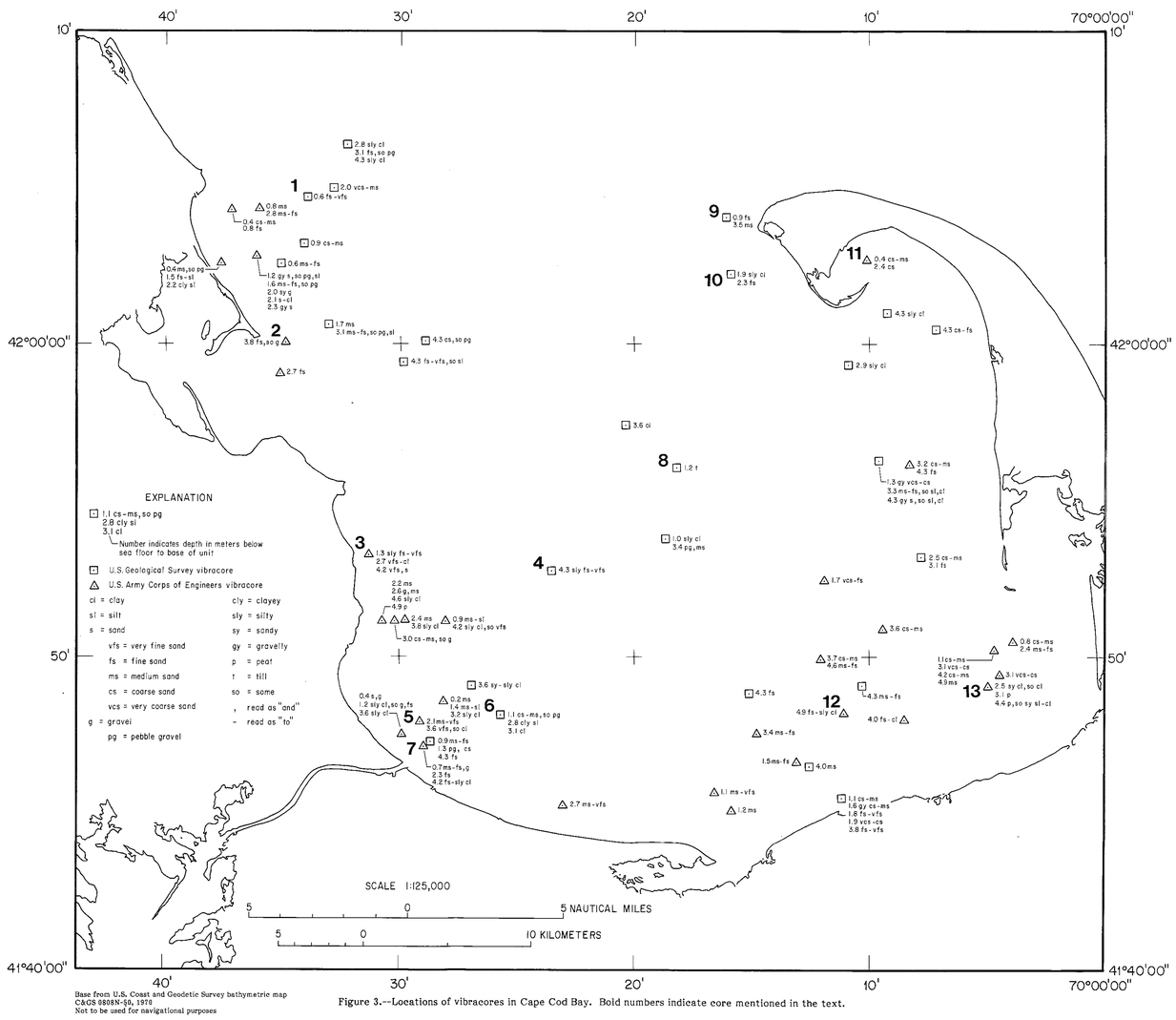
MAPS SHOWING THE GEOLOGY OF THE INNER CONTINENTAL SHELF, CAPE COD BAY, MASSACHUSETTS

By
Robert N. Oldale and Charles J. O'Hara
1990

Manuscript approved for publication December 5, 1989

INTERIOR--GEOLOGICAL SURVEY, RESTON, VA--1990

For sale by U.S. Geological Survey Map Distribution, Box 25286, Federal Center, Denver, CO 80225



Base from U.S. Coast and Geodetic Survey bathymetric map
C&GS 8808N-SD, 1970
Not to be used for navigational purposes

Figure 3.--Locations of vibracores in Cape Cod Bay. Bold numbers indicate core mentioned in the text.

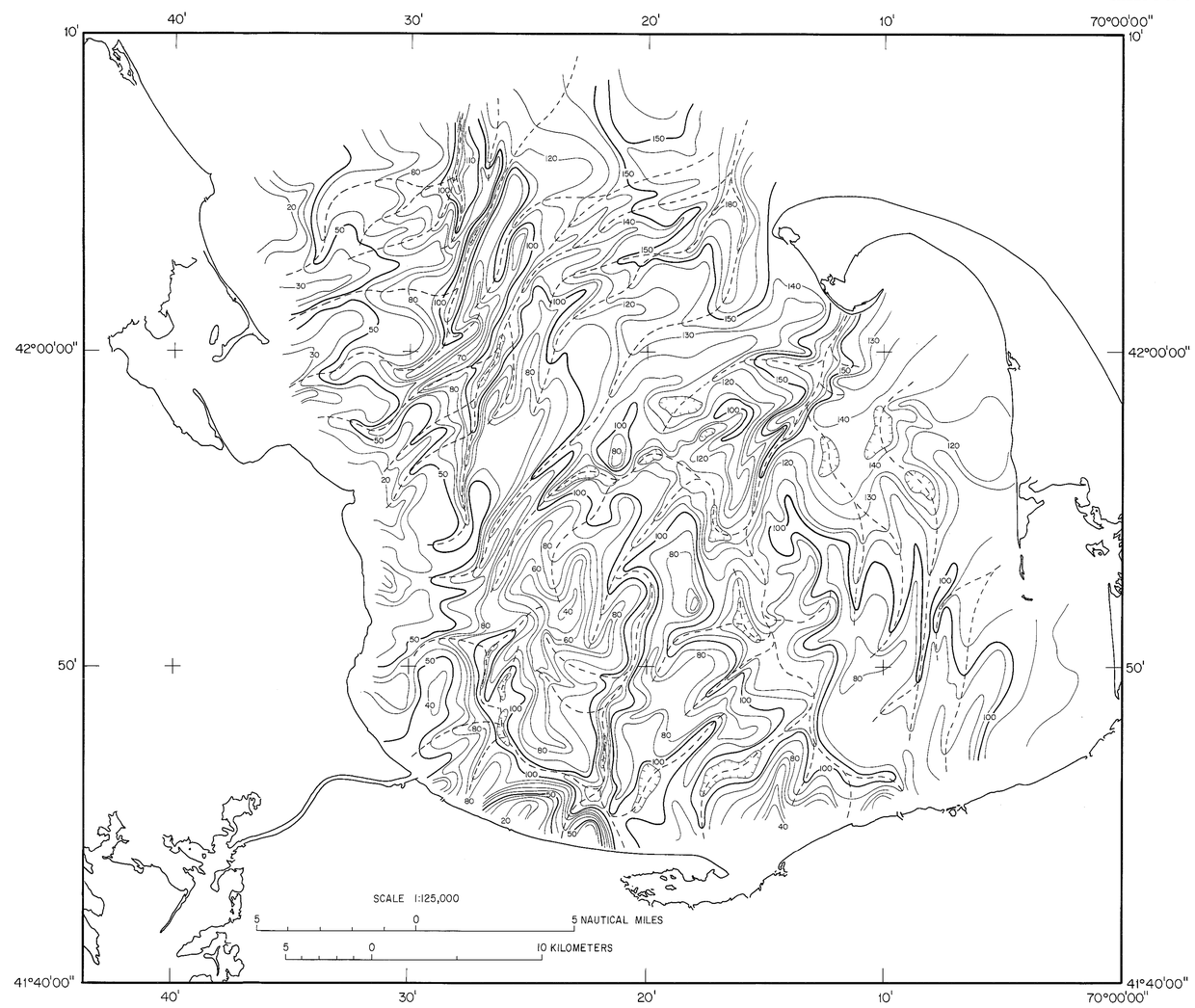


Figure 4.--Depth below sea level to basement surface. Depth based on inferred seismic velocities of 1.5 km/sec for water and sediments of Holocene age, 1.8 km/sec for sediments of Pleistocene age, and 2.5 km/sec for sediments of Tertiary or Cretaceous age. Contour interval 10 m. Dashed lines show thalweg location of bedrock valleys.

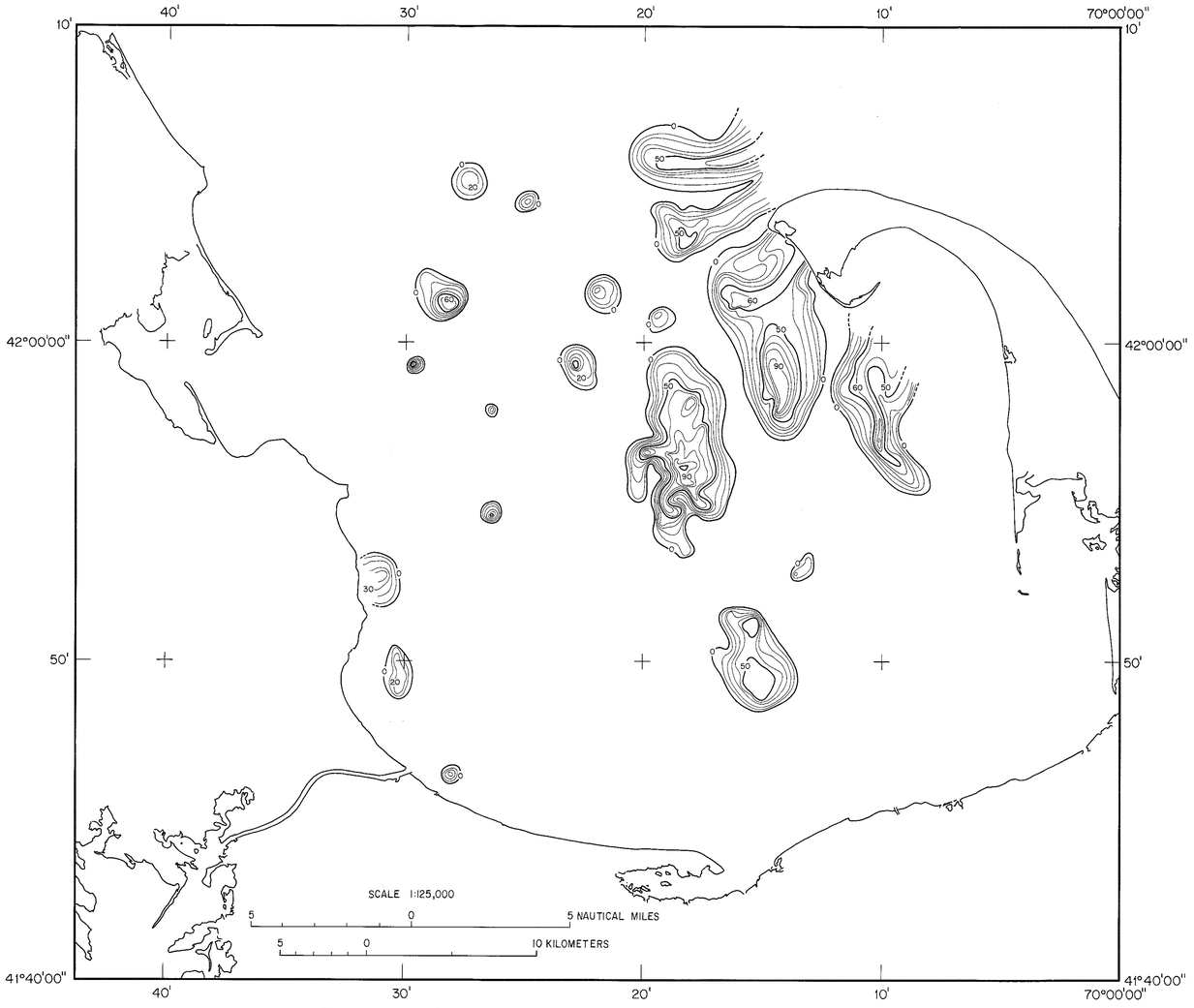


Figure 5.--Thickness of sediments inferred to be coastal plain sediments of Tertiary and Cretaceous age. Thickness based on an inferred seismic velocity of 2.5 km/sec. Contour interval 10 m.

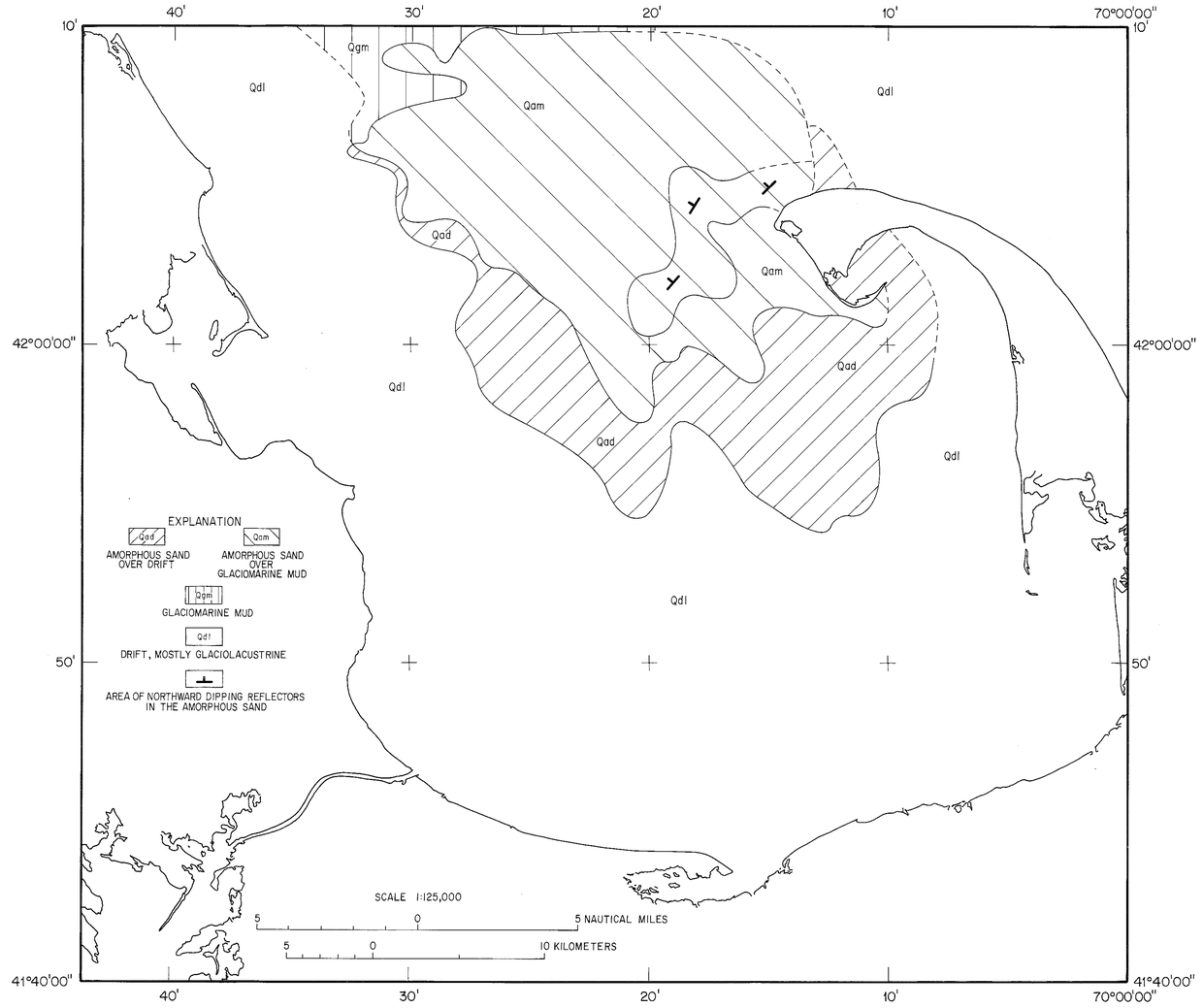


Figure 6.--Distribution of sediments of Pleistocene age exposed at the sea floor or overlain by sediments of Holocene age.

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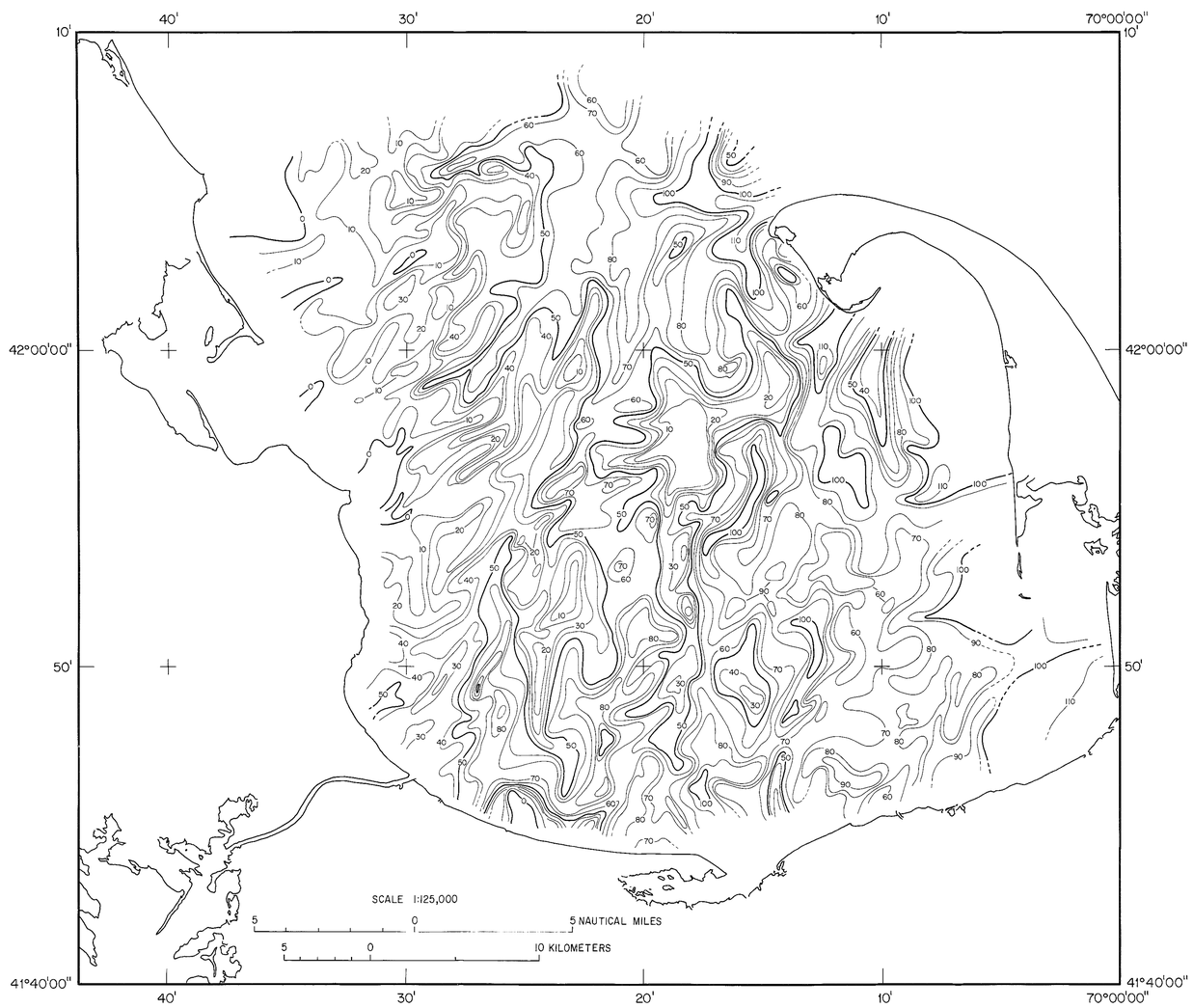

Figure 7.--Thickness of sediments of Pleistocene age. Based on an inferred seismic velocity of 1.8 km/sec. Contour interval 10 m.

Figure 8.--Depth below sea level to top of sediments of Pleistocene age. Based on an inferred seismic velocity of 1.5 km/sec for water and deposits of Holocene age. Contour interval 2 m. Dashed lines show thalweg location of valleys cut in the Pleistocene deposits.

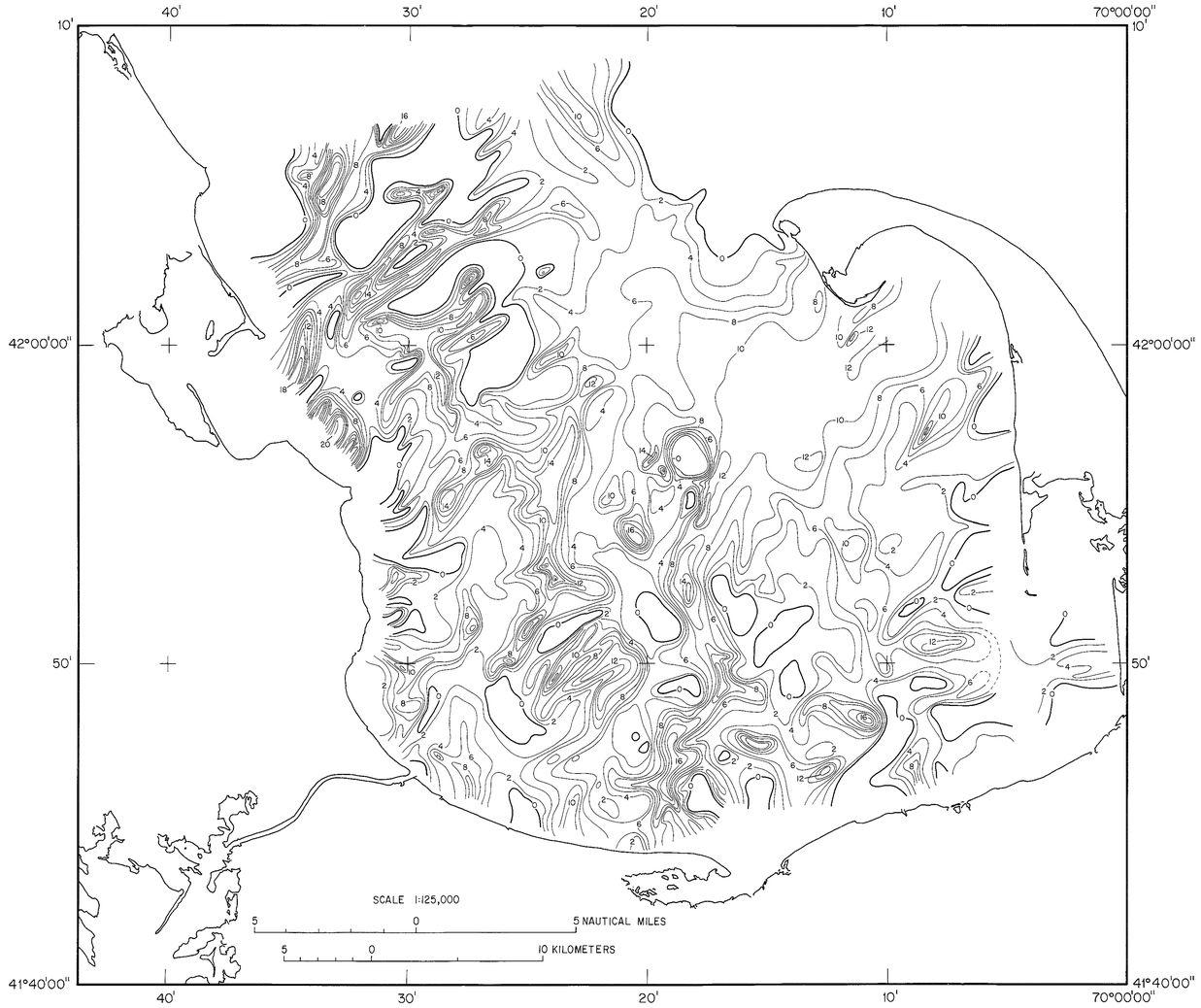

Figure 9.--Thickness of sediments of Holocene age. Based on an inferred seismic velocity of 1.5 km/sec. Contour interval 2 m.

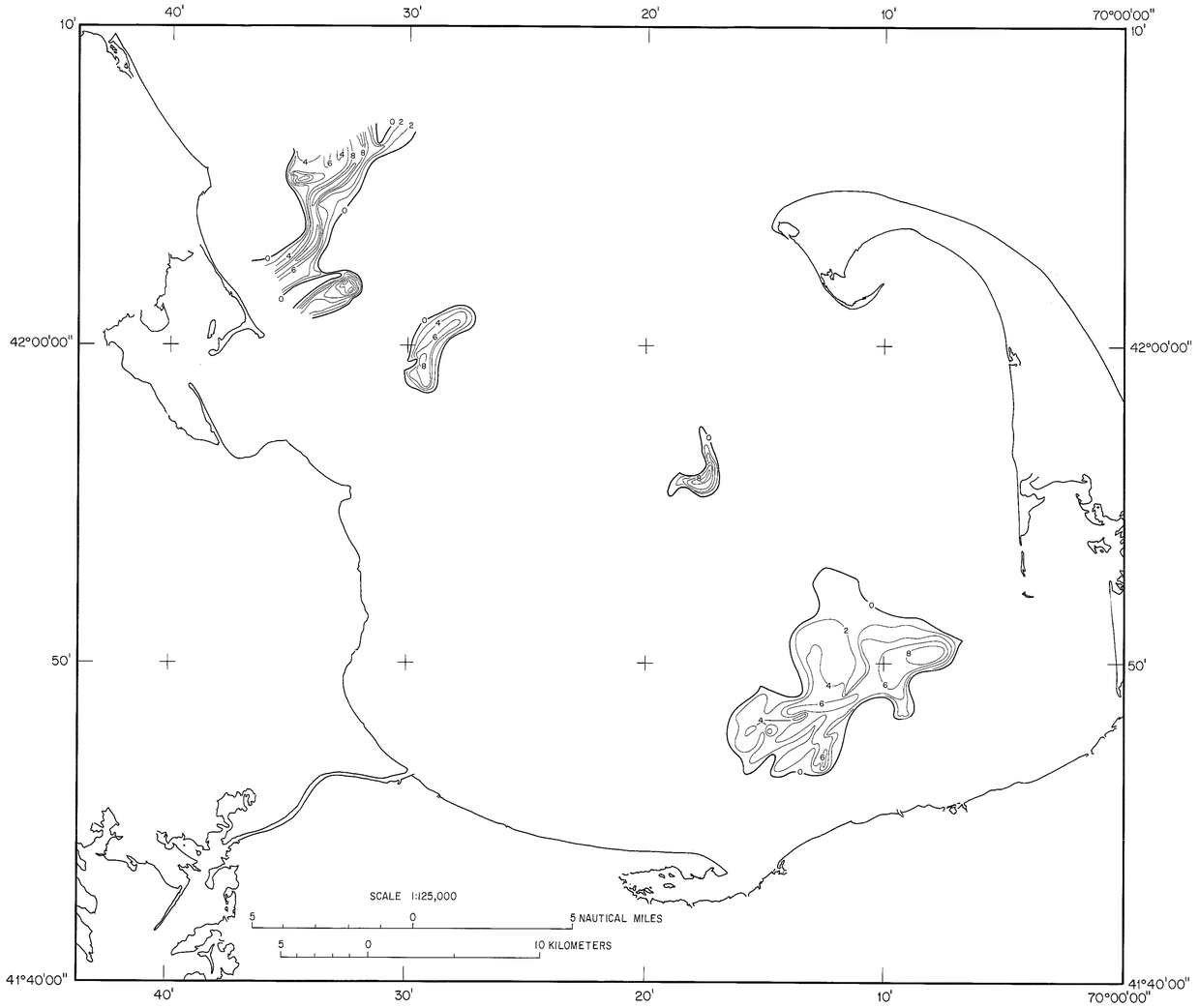

Figure 10.--Thickness and distribution of beach and bar deposits. Based on an inferred seismic velocity of 1.5 km/sec. Contour interval 2 m.

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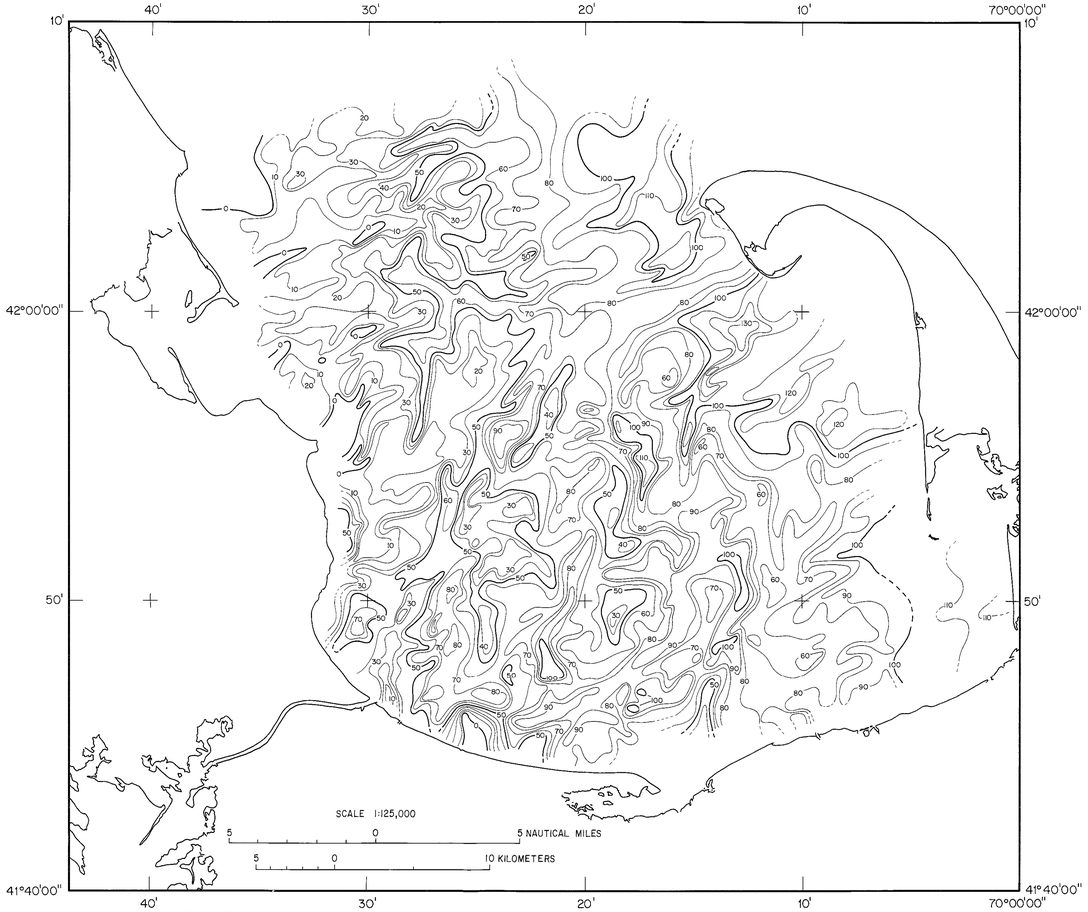


Base from U.S. Coast and Geodetic Survey bathymetric map
C&GS 8898N-66, 1970
Not to be used for navigational purposes

Figure 11.--Thickness of total sediment above bedrock. Based on inferred seismic velocities of 1.5 km/sec for sediments of Holocene age, 1.8 km/sec for sediments of Pleistocene age, and 2.5 km/sec for sediments of Tertiary or Cretaceous age. Contour interval 10 m.

CORRELATION OF MAP UNITS

Qm, Qb, Qob	Holocene	QUATERNARY
Unconformity (ru)		
Qf		
Unconformity (tu)		
Qd	Pleistocene	
Unconformity		
Tcp	Tertiary and Upper Cretaceous	PRE-QUATERNARY
Unconformity		
Pz	Triassic to Precambrian	

DESCRIPTION OF MAP UNITS

Qb Beach deposits (Holocene)--Mostly sand, some gravelly sand, and minor amounts of gravel. Scattered shells and shell fragments. Bedding mostly flat, locally foreset bedded. Grades offshore into silt and clay (deep water marine deposits). Generally less than 2 m thick. Overlies the transgressive unconformity (tu)

Qm Deep water marine deposits (Holocene)--Mostly silt and clay, some sand. Scattered shells and shell fragments. Bedding flat and continuous. Grades onshore into sand (beach deposits). Generally less than 12 m thick. Conformably overlies deposits of Pleistocene age in deepest part of the bay. Elsewhere overlies the transgressive unconformity (tu)

Qob Older beach or bar deposits (Holocene)--Mostly sand, some gravelly sand, and minor amounts of gravel. Scattered shells and shell fragments. Bedding mostly flat, locally foreset bedded. Generally less than 4 m thick. Overlies the transgressive unconformity (tu)

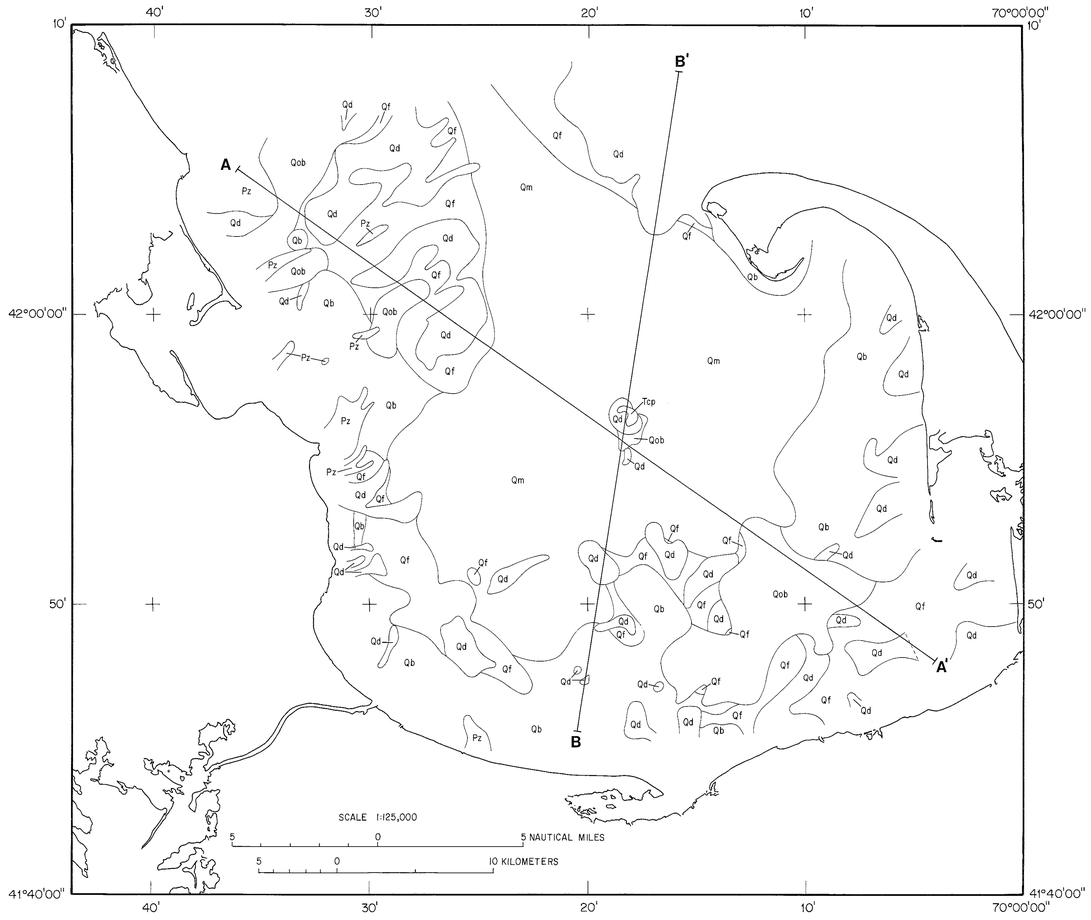
Qf Fluvial and estuarine deposits (Holocene)--Composed of fluvial sand and gravel, estuarine sand and mud, and freshwater and saltwater peat. Flat and foreset bedded. Generally less than 10 m thick. Underlies the transgressive unconformity (tu) and overlies the regressive unconformity (ru)

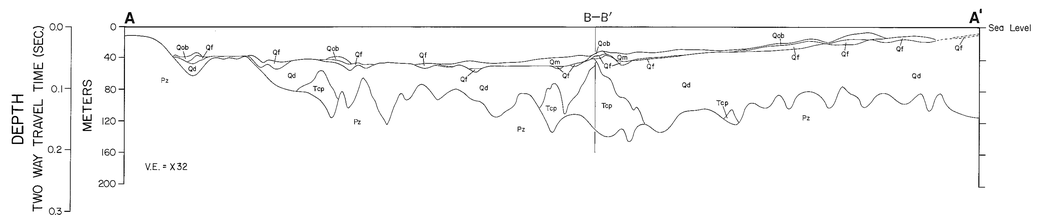
Qd Glaciolacustrine, glaciomarine, and marine deposits, undifferentiated (Pleistocene)--Glaciolacustrine deposits mostly gravelly sand. Includes scattered boulders, gravel, sand, and mud. May include till. Acoustically characterized by short irregular internal reflectors and locally by rhythmic acoustic laminations and parabolic reflectors. Probably planar and cross bedded. Glaciomarine deposits mostly mud, includes some sand and gravel. Rhythmically laminated to thin bedded. Marine deposits mostly sand, but probably includes some gravel and mud. Acoustically amorphous, locally characterized by reflectors that resemble delta foreset beds. Up to about 100 m thick. They underlie the transgressive (tu) and regressive (ru) unconformities and overlie bedrock and locally coastal plain deposits

Tcp Coastal plain deposits (Tertiary and Upper Cretaceous)--Inferred to be unconsolidated to consolidated gravel to clay similar to deposits that crop out to the west of the bay and on Martha's Vineyard. Up to about 100 m thick. Occur as isolated erosional remnants beneath the deposits of Quaternary age. Overlies bedrock

Pz Bedrock (Triassic to Precambrian [Proterozoic])--Igneous, metamorphic, and consolidated sedimentary rock

Contact--Dashed where approximately located





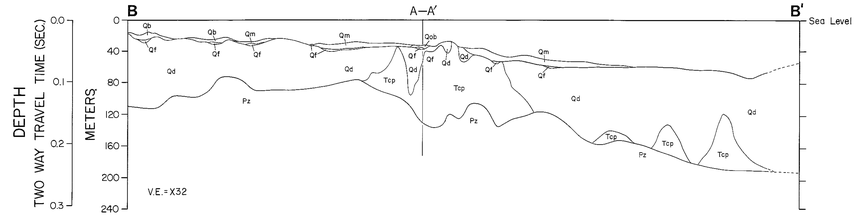


Figure 12.--Geologic map of Cape Cod Bay. Deposits of Holocene age too thin to be resolved in the seismic data may overlie pre-Holocene deposits in places.

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INTERIOR--GEOLOGICAL SURVEY, RESTON, VA--1990

April 13, 2009

MF-2118, Maps showing the geology of the inner continental shelf,
Cape Cod Bay, Massachusetts, 1990, Robert N. Oldale and
Charles J. O'Hara: 4 sheets: was scanned using an Ideal Contex HD4230 Plus color scanner
running NextImage vers. 1.0.2 software configured at 24 bit color,
300 dpi resolution for sheet 4 because of seismic profiles reproductions and at
300 dpi, black and white settings for sheets 1, 2, and 3, then saved as uncompressed
tif files to a Dell Optiplex GX280 Windows XP machine.

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